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Optimal Power Flow Solution of the Algerian Electrical Network using Differential Evolution Algorithm

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Abstrak

Makalah ini menyajikan algoritma evolusi diferensial (DE) sebagai solusi untuk masalah aliran daya optimal (OPF) pada sistem daya. Tujuan dari sistem tenaga listrik adalah untuk memberikan daya nyata untuk jumlah terbesar pengguna setiap saat pada biaya serendah mungkin. Jadi tujuannya adalah untuk meminimalkan biaya bahan bakar total dari unit-unit pembangkit dan juga menjaga kinerja sistem diterima dalam sisi batasan keluaran daya reaktif pembangkit, tegangan bus, parameter kompensator stati VAR (SVC) dan beban lebih pada jalur transmisi. Waktu komputasi CPU dapat direduksi dengan menguraikan masalah ke dalam dua sub-masalah. Sub-masalah pertama, meminimalkan biaya bahan bakar pembangkitan dan sub-masalah kedua adalah penyelesaian daya reaktif sehingga tegangan bus optimal dapat ditentukan dan mereduksi kerugian dengan mengendalikan perubahan keran dari transformator dan kompensator statis VAR (SVC). Untuk memverifikasi pendekatan yang diusulkan dan untuk tujuan perbandingan, simulasi pada jaringan Aljazair dengan 114 bus, 175 cabang (jalur dan transformer) dan 15 pembangkit. Hasil yang diperoleh menunjukkan bahwa DE adalah mudah digunakan, cepat, kuat dan merupakan teknik optimasi yang handal dibandingkan dengan metode optimasi global lainnya seperti PSO dan GA.

Kata kunci: *aliran daya optimal, evolusi diferensial, FACTS, jaringan listrik Aljazair, lisrik murah*

Abstract

This paper presents solution of optimal power flow (OPF) problem of a power system via differential evolution (DE) algorithm. The purpose of an electric power system is to deliver real power to the greatest number of users at the lowest possible cost all the time. So the objective is to minimize the total fuel cost of the generating units and also maintaining an acceptable system performance in terms of limits on generator reactive power outputs, bus voltages, static VAR compensator (SVC) parameters and overload in transmission lines. CPU times can be reduced by decomposing the problem in two subproblems, the first subproblem minimize the fuel cost of generation and the second subproblem is a reactive power dispatch so optimum bus voltages can be determined and reduce the losses by controlling tap changes of the transformers and the static VAR compensators (SVC). To verify the proposed approach and for comparison purposes, we perform simulations on the Algerian network with 114 buses, 175 branches (lines and transformers) and 15 generators. The obtained results indicate that DE is an easy to use, fast, robust and powerful optimization technique compared to the other global optimization methods such as PSO and GA.

Keywords: *economic power, optimal power flow, differential evolution, FACTS, Algerian network*

1. Introduction

The optimal power flow (OPF) can be defined as a typical flexible nonlinear programming problem with many objectives. Because of the increasing scale and constraint number of electric power system, the OPF has been a complicated large-scale mathematic programming problem. The optimal power flow (OPF) calculation optimizes the static operating condition of a power generation-transmission system. The main benefits of optimal power flow are (i) to ensure static security of quality of service by imposing limits on generation-transmission system's operation, (ii) to optimize reactive-power/voltage scheduling and (iii) to improve economy of operation through the full utilization of the system's feasible operating range and by the accurate coordination of transmission losses in the scheduling process. The OPF has been usually considered as the minimization of an objective function representing the generation cost and/or the transmission loss. The constraints involved are the physical laws governing the power generation-transmission systems and the operating limitations of the

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equipment. The optimal power flow has been frequently solved using classical optimization methods. Effective optimal power flow is limited by (i) the high dimensionality of power systems and (ii) the incomplete domain dependent knowledge of power system engineers [1-3].

In recent years, energy, environment, deregulation of power utilities have delayed the construction of both generation facilities and new transmission lines. Better utilization of existing power system capacities by installing flexible AC transmission systems FACTS devices has become imperative. The application of flexible alternative current transmission systems (FACTS) in electric power system, such as thyristor controlled series compensations (TCSC), thyristor controlled phase angle regulators (TCPR), unified power flow controllers (UPFC) and static VAR compensator (SVC), is intended for the control of power flow, improvement of stability, voltage profile management, power factor correction, loss minimization, and reduced cost of production. The OPF becomes even more complex when FACTS devices are taken into consideration as control variables.

It can be seen that the generalised OPF is a non-linear, no-convex, large-scale, static optimization problem with both continuous and discrete control variables. Applications of conventional optimisation techniques such as the gradient-based algorithms are not good enough to solve this problem. Because it depends on the existence of the first and the second derivatives of the objective function and on the well computing of these derivative in large search space.

A new floating point encoded evolutionary algorithm for global optimization and named it differential evolution (DE) was proposed by Storn and Price [4], and since then the DE algorithm has been used in many practical cases. The original DE was modified, and many new versions proposed. Generally DE is characterized as a simple heuristic of well-balanced mechanism with flexibility to enhance and adapt to both global and local exploration abilities. The effectiveness, efficiency and robustness of the DE algorithm are sensitive to the settings of the control parameters. The best settings for the control parameters depend on the function and requirements for consumption time and accuracy. It has gained a lot of attention in various power system applications. It is a population based method and an improved version of GA using similar operators: mutation, crossover and selection. The main difference in constructing better solutions is that GA relies on crossover while DE relies on mutation operation. The mutation operation is used as a search mechanism, which is based on the differences of randomly sampled pairs of solutions in the population. The algorithm uses selection operation to direct the search towards the prospective regions in the search space [5].

This paper proposes a simple approach based on DE algorithm implemented in C++ Builder to minimize the total fuel cost of the thermal generating units and also maintaining an acceptable system performance in terms of limits on generator reactive power outputs, bus voltages, static VAR compensator (SVC) parameters and overload in transmission lines. CPU times can be reduced by decomposing the problem in two subproblems, the first subproblem minimize the fuel cost of generation and the second subproblem is a reactive power dispatch so optimum bus voltages can be determined and reduce the losses by controlling tap ratio of the transformers and the static VAR compensators (SVC).

To verify the proposed approach and for comparison purposes, we perform simulations on the Algerian network with 114 buses, 175 branches (lines and transformers) and 15 generators. The obtained results indicate that ED is an easy to use, fast, robust and powerful optimization technique compared to other global optimization methods such as PSO, and GA.

2. Problem Formulation

In OPF, the generators are modelled as voltage controlled buses and loads as load buses. One generator serves as the slack bus. The standard OPF problem can be formulated as a constrained optimisation problem as follows:

$$\begin{aligned} \min \quad & f(x,u) \\ s.t. \quad & g(x,u) = 0 \\ & h(x,u) \le 0 \end{aligned} \tag{1}$$

where *f(x,u)* is the objective function, *g(x,u)* represents the equality constraints, *h(x,u)* represents the inequality constraints, x is the vector of the dependent variables such us the voltage and angle of load buses and *u* is the vector of the control variables such as generator real power *Pg*, generator voltages Vg, transformer tap setting *T*, and the reactance of dynamic shunt capacitors/reactors B_{SVC} . Therefore, u can be expressed as

$$u = \left[P_g, V_g, t, B_{SVC}\right]^T \tag{2}$$

2.1. Objective Function

The Optimal power flow problem with consideration of FACTS devices can be decomposed in two sub-problems which are the Economic power Dispatch and the Reactive Power Flow combined with FACTS devices.

2.1.1. Economic Objective Function

The essence of the optimal power flow problem resides in reducing the objective function and simultaneously satisfying the load flow equations (equality constraints) without violating the inequality constraints

The most commonly used objective in the OPF problem formulation is the minimisation of the total operation cost of the fuel consumed for producing electric power within a schedule time interval (one hour). The individual costs of each generating unit are assumed to be function, only, of real power generation and are represented by quadratic curves of second order. The objective function for the entire power system can then be expressed as the sum of the quadratic cost model at each generator [6], [7].

$$F_{ec}(x) = \sum_{i=1}^{ng}\left(\alpha_i + \beta_i Pg_i + \gamma_i Pg_i^2\right) \text{ \$/h} \tag{3}$$

where α_i, β_i and γ_i are the cost coefficients of generator at bus i.

2.1.1.1. Active Power Transmission Losses and Voltage Deviation Objective Function

The objective is to minimise the active power losses in the transmission network and/or the voltage deviations at the load buses involving reactive power controls, while fixing active power controls.

The tap changers of the transformers and SVC can control the reactive power flow so optimum bus voltages can be determined and reduce the losses. The shunt FACTS device should be placed on the most sensitive buses. The insertion of SVC enhances the voltages at various buses, and reduction power loss of the system. For SVC, it can provide reactive power and voltage support. As a result, the reactive power generation of SVC becomes one of the control variables. One of the important indices of power system security is the bus voltage magnitude. The voltage magnitude deviation from the desired value at each load bus must be as small as possible.

(i) The active power transmission losses (P_{loss}) is given by:

$$P_{loss} = \sum_{k=1}^{N_l} g_k\left[(t_k V_i)^2 + V_j^2 - 2t_k V_i V_j \cos\theta_{ij}\right] \tag{4}$$

where N_l is number of branch on the network, t equal =1 if the branch is a transmission line and t equal the tap ratio value if the branch is a transformer, k is a branch with conductance g connecting the ith bus to the jth bus.

(ii) The deviation of voltage is given as follows:

$$\Delta V = \sum_{k=1}^{N_{PQ}}\left|V_k - V_k^{des}\right| \tag{5}$$

where N_{PQ} is the number of load buses and V_k^{des} is the desired or target value of the voltage magnitude at load bus k.

(iii) The total objective function of OPF problem.

The equation of the total objective function using into account the Economic Power Dispatch (ED) objective function; active power transmission losses (P_{loss}); and the sum of the normalized violations of voltages (F_{Vi}) is as follow:

$$f = F_{ED} + \omega_l P_{loss} + \omega_V F_V \tag{6}$$

where $F_V = \sum_{j=1}^{N_{PQ}} \left(\left|V_{PQj} - V_{PQj}^{\lim}\right|\right) / \left(\left|V_{PQj}^{\max} - V_{PQj}^{\min}\right|\right)$

ω_l and ω_V constants are related to line loss and voltage deviation. These constants were found as a result of trials.

2.1.2. Types of Equality Constraints

While minimising the objective function, it is necessary to make sure that the generation still supplies the load demands plus losses in transmission lines. The equality constraints are the power flow equations describing bus injected active and reactive may be defined as follows:

$$P_i = Pg_i - Pd_i = \sum_{j=1}^{nb} V_i V_j \left(g_{ij} \cos\theta_{ij} + b_{ij} \sin\theta_{ij}\right) \tag{7}$$

$$Q_i = Qg_i - Qd_i = \sum_{j=1}^{nb} V_i V_j \left(g_{ij} \sin\theta_{ij} - b_{ij} \cos\theta_{ij}\right) \tag{8}$$

where Pg_i ,Qg_i are the active and reactive power generation at bus i; Pd_i , Qd_i are the real and reactive power demands at bus i; V_i , V_j , the voltage magnitude at bus i,j, respectively; θ_{ij} is the admittance angle, b_{ij} and g_{ij} are the real and imaginary part of the admittance and nb is the total number of buses. The equality constraints are satisfied by running Newton-Raphson algorithm.

2.1.3. Types of Inequality Constraints

The inequality constraints of the OPF reflect the limits on physical devices in the power system as well as the limits created to ensure system security. The most usual types of inequality constraints are upper bus voltage limits at generations and load buses, lower bus voltage limits at load buses, var. limits at generation buses, maximum active power limits corresponding to lower limits at some generators, maximum line loading limits and limits on transformer tap setting. The inequality constraints on the problem variables considered include: (1) upper and lower bounds on the active generations at generator buses $Pg_i^{min} \le Pg_i \le Pg_i^{max}$, *i= 1, ng*, (2) upper and lower bounds on the reactive power generations at generator buses $Qg_i^{min} \le Qg_i \le Qg_i^{max}$, *i = 1, ng,* (3) upper and lower bounds on reactive power injection at buses with VAR compensation $Qc_i^{min} \le Qc_i \le Qc_i^{max}$, *i=1, nc,* (4) Upper and lower bounds on the voltage magnitude at the all buses. $V_i^{min} \le V_i \le V_i^{max}$, *i=1, nb,* (5) upper and lower bounds on the bus voltage phase angles θιμιν≤ θι ≤ θιμαξ , i = 1, nb; and (6) for secure operation, the transmission line loading Sl is restricted by its upper limit as:$S_{li} \le S_{li}^{max}$, *i = 1, nl*, where S_{li}, S_{li}^{max} are stand for the power of transmission line and limit of transfer capacity of transmission line and *nl* is the number of transmission lines.

The constraints on the state variables can be taken into consideration by adding penalty function to the objective function.

2.1.4. Application of FACTS in Electric Power System

The purpose of the transmission network is to pool power plants and load centres in order to supply the load at a required reliability and maximum efficiency at a lower cost. As power transfer grow, the power system can become increasingly more difficult to operate, and the system becomes more insecure with unscheduled power flows and higher losses. In this context, a concept called a flexible alternative current transmission system was introduced. The conception of flexible ac transmission systems (FACTS) as a total network control philosophy was first introduced by N. G. Hingorani [8] from the Electric power research institute (EPRI) in the USA in 1988, although the power electronic controlled devices had been used in the transmission network for many years before that.

The application of FACTS in electric power system is intended for the control of power flow, improvement of stability, voltage profile management, power factor correction, and loss minimization [9-12]. Power flow through an ac line is a function of phase angle, line and voltages and line impedance. The consequences of lack control over any of these variables are problems with stability, undesirable power flows, undesirable Var flows, higher losses, high or less voltage and among the others; with FACTS devices we can control the phase angle, the magnitude at chosen bus and line impedance.

Thyristor Controlled Series Capacitors (TCSC) and Static VAR compensators (SVC) are the most popular devices of the FACTS [13]. The main functionality of the SVC is to regulate the voltage at a chosen bus by controlling the reactive power injection at the location. Maintaining the rated voltage levels is important for proper operation and utilization of loads. Under voltage causes deregulation in the performance of loads such as induction motors, light bulbs, etc. Whereas over voltage causes magnetic saturation and resultant harmonic generation, as well as equipment failures due to insulation breakdown. These devices are characterized by rapid response, wide operational range and high reliability.

2.1.5. *Modeling of Static VAR Compensator*

Thyristor controlled Static VAR compensators (SVCs) were developed in the 1970s to act as compensation for arc furnaces, these devices are one of the earliest types of Flexible AC Transmission System (FACTS) controllers. The typical shunt connected SVC consists of thyristor controlled reactors and thyristor switched capacitors. The full continuous range of the SVC can be accessed by coordinating the switching of the discrete capacitor block and the continuous reactor controls [14].

The SVC is usually operated in a voltage regulating mode, which adjusts its susceptance to maintain the local transmission network voltage to a voltage setpoint value. The SVC can also operate in a constant MVAr mode, which maintains a fixed value of susceptance under steady state conditions. The effect of the SVC controller on the economic operation and voltage stability of the network is the principle motivation behind incorporating the SVC into various formulations. In this study, when the SVC is installed in the transmission line, it can be treated as a PV bus with the generation of real power as 0. The algebraic equation (9) gives the reactive power injected at the SVC bus i. The reactance B_{svc} is locked if one of its limits is reached.

$$Q = B_{svc} / V^2 \tag{9}$$

2.2. Application of DE Algorithm on OPF Problem

DE is a direct search method using operators: mutation, crossover and selection. The algorithm randomly chooses a population vector of fixed size. During each iteration of algorithm a new population of same size is generated. It uses mutation operation as a search mechanism. This operation generates new parameter vector by adding a weighted difference vector between two population members to a third member. In order to increase the diversity of the parameter vectors, the crossover operation produces a trial vector which is a combination of a mutant vector and a parent vector. Then the selection operation directs the search toward the prospective regions in the search space. In addition, the best parameter vector is evaluated for every generation in order to keep track of the progress that is made during the minimization process. The above iterative process of mutation, crossover and selection on the population will continue until a user-specified stopping criterion, normally, the maximum number of generations or the maximum number of function evaluations allowed is met. The process is assumed to have converged if the difference between the best function values in the new and old population, and the distance between the new best point and the old best point are less than the specified respective tolerances. The other type of stopping criterion could be if the global minimum of the problem is know a-priori. Then DE will be terminated if the difference between the best function value in the new population and the known global minimum is less than the user defined tolerance level [15].

DE is a simple real parameter optimization algorithm. It works through a simple cycle of stages, presented in Figure 1.

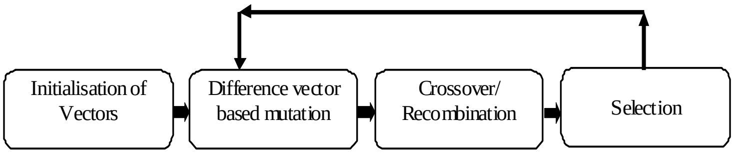

Figure 1. Main stages of the DE algorithm

2.2.1 Differential Evolution optimization process

Differential Evolution uses a population P of size N^P that evolves over G generations to reach the optimal solution. Each individual Xi is a vector that contains as many parameters as the problem decision variables D.

$$P^{(G)} = \left[X_1^{(G)}, \ldots\ldots, X_{Np}^{(G)} \right] \tag{10}$$

$$X_i^{(G)} = \left[X_{1,i}^{(G)}, \ldots\ldots, X_{D,i}^{(G)} \right]^T \quad i = 1, \ldots, N_p \tag{11}$$

The population size NP is an algorithm control parameter selected by the user which remains constant throughout the optimization process. The optimization process in DE is carried out using the three basic operations: mutation, crossover and selection.

2.2.1.1. Initialization

At the early stage of DE search, i.e., t = 0, the algorithm starts by creating an initial population of NP vectors.

The problem independent variables are initialized somewhere in their feasible numerical range in every vector as follows.

$$X_{j,i}^{(0)} = X_j^{\min} + rand(0,1) \cdot \left(X_j^{\max} - X_j^{\min} \right) \tag{12}$$

where $i = 1, \ldots, N_P$ and $j = 1, \ldots, D$; $X_j^{\min}$ and $X_j^{\max}$ are the lower and upper bounds of the jth decision parameter; and $rand(0,1)$ is a uniformly distributed random number within [0, 1] generated for each value of j. $X_{j,i}^{(0)}$ is the jth parameter of the ith individual of the initial population.

2.2.1.2. Mutation

The mutation operator creates mutant vectors $\left(X_i^{'} \right)$ by perturbing a randomly selected vector Xa with the difference of two other randomly selected vectors Xb and Xc

$$X_i^{'(G)} = X_a^{(G)} + F\left(X_b^{(G)} - X_c^{(G)} \right) \; i = 1, \ldots, N_P \tag{13}$$

where Xa Xb and Xc are randomly chosen vectors among the Np population, and $a \neq b \neq c \neq i$. The scaling constant F is an algorithm control parameter used to adjust the perturbation size in the mutation operator and to improve algorithm convergence. Typical value of F is in the range of 0.4–1.0.

2.2.1.3. Crossover

Two types of crossover schemes can be used by DE algorithm. These are exponential crossover and binomial crossover. Although the exponential crossover was presented in the original work of Storn and Price [16], the binomial variant is much more used in recent applications.

In exponential type, the crossover operation generates trail vectors $\left(X_i^{''}\right)$ by mixing the parameters of the mutant vectors $\left(X_i^{'}\right)$ with the target vector $\left(X_i\right)$ according to a selected probability distribution,

$$X_{j,i}^{''(G)} = \begin{cases} X_{j,i}^{'(G)}, & if \quad \eta_j^{'} \le C_R \quad or \quad j = q \\ X_{j,i}^{(G)}, & otherwise \end{cases} \tag{14}$$

where $i = 1,....., N_P$ and $j = 1,....., D$; q is a randomly chosen index $\in \{1,....., N_P\}$ that guarantees that the trail vector gets at least one parameter from the mutant vector; $\eta_j^{'}$ is a uniformly distributed random number within [0, 1] generated for each value of j.The crossover constant CR is an algorithm parameter that controls the diversity of the population and aids the algorithm to escape from local minima. $X_{j,i}^{(G)}, X_{j,i}^{'(G)}$ and $X_{j,i}^{''(G)}$ are the jth parameter of the ith target vector, mutant vector and trail vector at generation G, respectively.

2.2.1.4. Selection

To keep the population size constant over subsequent generations, the selection process is carried out to determine which one of the child and the parent will survive in the next generation.

The selection operation forms the population by choosing between the trail vectors and their predecessors (target vectors) those individuals that present a better fitness or are more optimal according to (18).

$$X_i^{(G+!)} = \begin{cases} X_i^{''(G)} & if \quad f\left(X_i^{''(G)}\right) \le f\left(X_i^{(G)}\right) \\ X_i^{(G)} & otherwise \end{cases}, i = 1,......, N_P \tag{15}$$

This process is repeated for several generations allowing individuals to improve their fitness as they explore the solution space in search of optimal values.

DE has three essential control parameters: the scaling factor (F), the crossover constant (CR) and the population size (NP). The scaling factor is a value in the range [0, 2] that controls the amount of perturbation in the mutation process. The crossover constant is a value in the range [0,1] that controls the diversity of the population. The population size determines the number of individuals in the population and provides the algorithm enough diversity to search the solution space.

Proper selection of control parameters is very important for algorithm success and performance. The optimal control parameters are problem specific. Therefore, the set of control parameters that best fit each problem have to be chosen carefully. The most common method used to select the control parameter is parameter tuning. Parameter tuning adjusts the control parameters through testing until the best settings are determined. Typically the following ranges are good initial estimates: [15]: F= [0.5, 0.6], CR= [0.75, 0.90] and NP= [3D, 8D].

In order to avoid premature convergence, F or NP should be increased, or CR should be decreased. Larger values of F result in larger perturbation and better probabilities to escape from local optima, while lower CR preserves more diversity in the population thus avoiding local optima.

2.2.2. DE Implementation for OPF

While applying DE to solve the OPF problem, the following issues need to be addressed: representation of the problem variables and formation of the evaluation function. These two issues are described in this section.

2.2.2.1. Problem Representation

Each vector in the DE population represents a candidate solution of the given problem. The elements of that solution consist of all the optimization variables of the problem. For the case of minimization of cost the generator active powers are the optimization variables. For the reactive power planning problem under consideration, generator terminal voltages $\left(V_{gi}\right)$ the transformer tap positions (tk) and the Capacitor settings (QCi) are the optimization variables. Generator bus voltage is represented as floating point numbers, whereas the transformer tap position and reactive power generation of capacitor are represented as integers.

2.2.2.2. Evaluation Function

Differential evolution searches for the optimal solution by maximizing a given fitness function, and therefore an evaluation function which provides a measure of the quality of the problem solution must be provided. The objective is to minimize the total cost while satisfying all constraints. The equality constraints are satisfied by running the Newton Raphson power flow algorithm. The inequality constraints on the control variables are taken into account in the problem representation itself, and the constraints on the state variables are taken into consideration by adding a quadratic penalty function to the objective function. With the inclusion of penalty function the new objective function becomes,

$$Min\,F = f + SP + \sum_{j=1}^{N_{PQ}} VP_j + \sum_{j=1}^{N_\tau} QP_j + \sum_{j=1}^{N_1} LP_j \qquad (16)$$

Here, SP, VP_j ,QP_j and LP_j are the penalty terms for the reference bus generator active power limit violation, load bus voltage limit violation; reactive power generation limit violation and line flow limit violation respectively. These quantities are defined by the following equations:

$$SP = \begin{cases} K_s\left(P_s - P_s^{\max}\right)^2 \; if \;\; P_s > P_s^{\max} \\ K_s\left(P_s - P_s^{\min}\right)^2 \; if \;\; P_s < P_s^{\min} \\ 0 \qquad\qquad otherwise \end{cases} \qquad (17)$$

$$VP_j = \begin{cases} K_v(V_j - V_j^{\max})^2 \;\; if \;\; V_j > V_j^{\max} \\ K_v(V_j - V_j^{\min})^2 \;\; if \;\; V_j < V_j^{\min} \\ 0 \qquad\qquad otherwise \end{cases} \qquad (18)$$

$$QP_j = \begin{cases} K_q(Q_j - Q_j^{\max})^2 \;\; if \; Q_j > Q_j^{\max} \\ K_q(Q_j - Q_j^{\min})^2 \;\; if \; Q_j < Q_j^{\min} \\ 0 \qquad\qquad otherwise \end{cases} \qquad (19)$$

$$LP_j = \begin{cases} K_l(L_j - L_j^{\max})^2 \;\; if \; L_j > L_j^{\max} \\ 0 \qquad\qquad otherwise \end{cases} \qquad (20)$$

where, K_s, K_v, K_q and K_l are the penalty factors. Since DE maximizes the fitness function, the minimization objective function f is transformed to a fitness function to be maximized as,

$$\text{Fitness} = k/F \qquad (21)$$

where *k* is a large constant.

3. Application Study

The OPF using DE method has been developed and implemented by the use of C++Builder2009 software, tested with Intel Pentium Dual CPU 2220, 2.4 GHz, 2GB RAM. Consistently acceptable results were observed. Initially, several runs are done with different values of DE key parameters such as differentiation (or mutation) constant F, crossover constant CR, size of population NP, and maximum number of generations GEN which is used here as a stopping criteria. In this paper, the following values are selected as: F=0.9: CR=0.9; NP=30; GEN=50. The proposed method is applied to two test systems.

The DE-OPF has also been tested on the Algerian network. It consists of 114 buses, 15 generators, 159 transmission lines and 16 transformers (Figure 2).

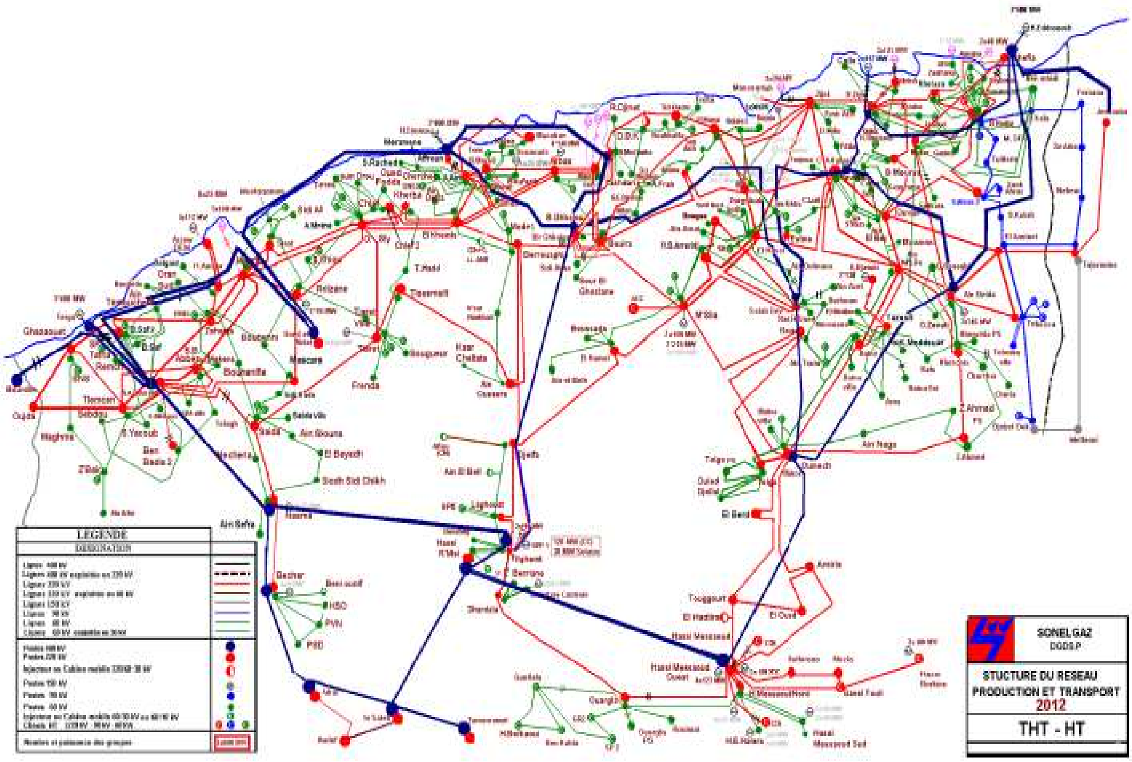

Figure 2. The topologies of the Algerian network

The Table 1 shows the technical and economic parameters of 15 ten generators of the Algerian electrical network. Knowing that the generator of the bus of N°=04 is the slack bus. The voltage of generator buses and load buses in the system are between [1, 1.1] and [0.90, 1.1], respectively.

In this test, in order to reduce the CPU time because the Algerian network is relatively large, the OPF problem is decomposed in two subproblems, the first subproblem minimize the fuel cost of generation and environmental pollution and the second subproblem is a reactive power dispatch so optimum bus voltages can be determined and reduce the losses by controlling generator voltages, tap ratio of the transformers and the static VAR compensators (SVC). The comparisons of the results obtained by the proposed approach DE, with those found by GA and PSO algorithms are reported in the Table 2.

In this case we minimize the fuel cost generation using into account the control vector composed only of the active powers of the generators. The results obtained with the proposed approach are better than those obtained by PSO and are very comparable to the results obtained by GA. The DE gives a more important profit in fuel cost of 19203,34$/h compared to the result obtained from PSO (19235 $/h) and are equal to the results of GA. The optimum value has been obtained at a comparable time (70 sec) compared to the execution time of PSO (75 sec) with 250 iterations.

Table 1. Power generation limits and cost coefficients for Algerian network

Bus Number	Pmin [MW]	Pmax [MW]	a [$/hr]	b [$/MWhr]	c [$/MW^{2}hr]
4	135.0000	1350	0	1.5000	0.0085
5	135.0000	1350	0	1.5000	0.0085
11	10.0000	100	0	2.5000	0.0170
15	30.0000	300	0	2.5000	0.0170
17	135.0000	1350	0	1.5000	0.0085
19	34.5000	345	0	2.5000	0.0170
52	34.5000	345	0	2.5000	0.0170
22	34.5000	345	0	2.5000	0.0170
80	34.5000	345	0	2.5000	0.0170
83	30.0000	300	0	2.5000	0.0170
98	30.0000	300	0	2.5000	0.0170
100	60.0000	600	0	2.0000	0.0030
101	20.0000	200	0	2.0000	0.0030
109	10.0000	100	0	2.5000	0.0170
111	10.0000	100	0	2.5000	0.0170

Tabel 2. Comparison of the results obtained by global methods of 114 Algerian electrical network

(MW)	**Pmin [MW]**	**AG**	**PSO**	**DE**	**Pmax [MW]**
Pg4)	135.0	515.11	515.8825	462.3908	1350
Pg5	135.0	241.9	441.4111	459.5589	1350
Pg11	10.0	99.9	100.0000	99.9431	100
Pg15	30.0	135.07	186.9059	192.5196	300
Pg17	135.0	674.04	449.1401	453.0142	1350
Pg19	34.5	163.76	206.6362	196.6569	345
Pg52	34.5	211.16	190.3105	189.0239	345
Pg22	34.5	277.06	177.8684	193.9372	345
Pg80	34.5	228.37	224.2734	192.1215	345
Pg83	30.0	182.49	188.7075	188.1283	300
Pg98	30.0	153.95	192.8819	189.0847	300
Pg100)	60.0	598.41	600.0000	599.9752	600
Pg101	20.0	197.54	200.0000	199.9703	200
Pg109	10.0	98.11	99.7997	99.9909	100
Pg111	10.0	39.46	100.0000	99.9415	100
Ploss		89.345	87.9052	89.2570	
Cost[$/hr]		19203	19235	19203.34	
time (sec)		290	70	75	

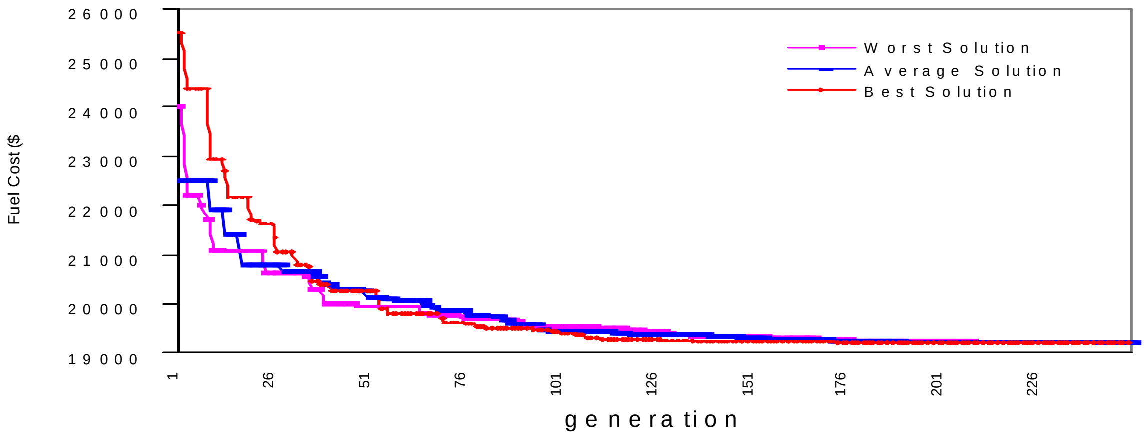

Figure 3. Convergence of DE-based OPF solutions algorithm for the Algerian network

Table 3. Comparison of the results obtained by DE with & without regelation of tap change and SVC control

	DE (w/o) Tap & SVC control	DE with Tap &SVC control
Pg4(MW)	*462.3908*	434.68
Ploss(MW)	*89.2570*	61.550
Cost[$/hr]	19203.34	18950.514

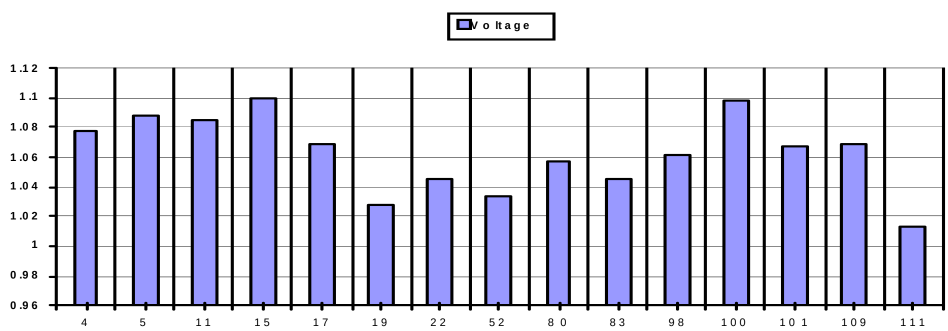

Figure 4. Optimal values of voltages of generators of 114 Algerian electrical network by the DE-based OPF

The DE is very fast than GA since the GA execution time is about 290 sec. A better cost value can be found by DE with 300 iterations which is 19202.86 $/hr.

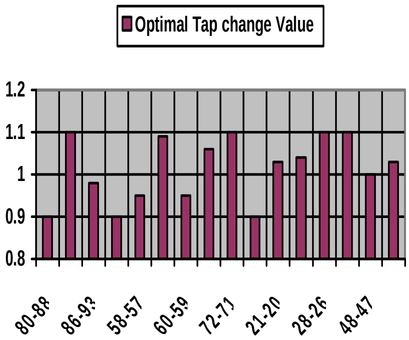

Figure 5. The optimal tap change values of transformers of the Algerian network

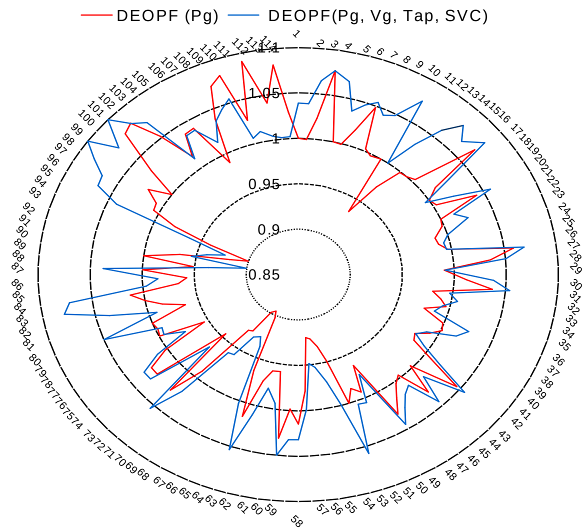

Figure 6. Voltage profile of all buses for the Algerian network with & without FACTS device

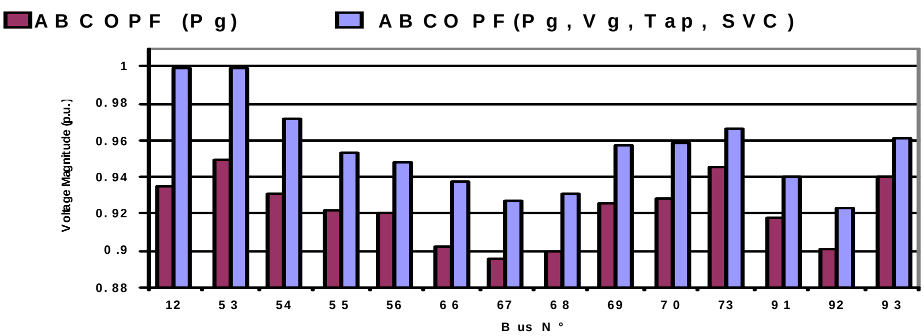

Figure 7. Voltage magnitude in the critical buses with and without the include of SVC in the bus 86

Figure 3 shows the typical convergence characteristics for the best solutions, worst solutions and the average solutions obtained for each generation. It can be seen that the convergence is fast for the proposed DE. The deviation is little between the worst and the best value of the optimum. In this test system according to results obtained from the continuation load flow to enhance the reactive power planning for the Algerian Network, the SVC Compensators can be installed at these critical buses 12, 53, 54, 55, 66, 67, 68, 69, 70, 73, 91, 92, 93. The DE algorithm based on the objective function which takes into account the power losses with only one SVC installed provides bus 68 as the optimum location.

Based on the Table 3, if we don't use the regulation of the transformer tap change and the SVC device the cost was 19203.34 $/MWh and the losses value was 89.257 MW compared with the case of compensation the cost was reduced to 18950.514 $/MWh and the losses value was reduced to 61.550 MW. The active power generation for the slack bus was reduced from 462.3908 MW to 434.68 MW. The optimal values of the voltage generators by DE are shown in the Figure 4. The optimal tap changes of the 16 transformers of the Algerian network after optimisation by DE are shown in the Figure 5.

The security constraints are also checked for voltage magnitudes and angles. All voltage magnitudes of the Algerian Network are between their minimum and the maximum values (Figure 6). No load bus was at the lower limit of the voltage magnitudes (0.9 p.u). The Figure 7 shows the voltage profile magnitude improvement at critical buses.

4. Conclusion

In this paper, DE optimization has been presented and applied to economic power dispatch. The de algorithm for solving the OPF has the control over the global and local exploration capabilities. This improves the search efficiency, overcomes premature convergence and avoids getting trapped into the local optima. It does not depend on the nature of the function it minimizes. Thus approximations made in traditional methods can be avoided. And it is insensitive to the initial searching points, thereby ensuring quality solution for different trial runs. To verify the proposed approach and for comparison purposes, we perform simulations on the Algerian Network system. The obtained results indicate that DE is an easy to use, fast, robust and powerful optimization technique compared with Particle Swarm Optimization (PSO) and Genetic Algorithms. Simulation results show that the DE is able to minimize the total cost along with minimization of loss in the system with mixed control variables (discrete and continuous). Also, it is found that DE obtains a better solution in reduced time. The result show also that installing SVC in right location can significantly enhance the security of power system by minimizing the overloaded lines, the bus voltage limit violations and power losses.

References

[1] Momoh A., El-Hawary M. E. and Adapa R. A Review of Selected Optimal Power Flow Literature to 1993 Part i: Nonlinear and Quadratic Programming Approaches. *IEEE Transaction on Power Systems*. 1999; 14(1): 96-104.
[2] Momoh A., El-Hawary M. E., and Adapa R. A Review of Selected Optimal Power Flow Literature to 1993 Part ii: Newton, Linear Programming and Interior Points Methods. *IEEE Transaction on Power Systems.* 1999; 14(1): 105-111.
[3] Dommel H. W., Tinney W. F. Optimal Power Flow Solutions. *IEEE Transactions on Power Apparatus and Systems*. 1968; 87(10): 1866-1876.
[4] Storn R., Price K. Differential Evolution —a Simple and Efficient Adaptive Scheme for Global Optimization over Continuous Spaces. Technical Report TR-95-012, ICSI, 1995.
[5] Storn R. Differential Evolution, A Simple and Efficient Heuristic Strategy for Global Optimization over Continuous Spaces. *Journal of Global Optimization*. 1997; 11: 341–359.
[6] Wood A. J. and B.F. Wollenberg. Power Generation, Operation and Control. 2nd Edition. John Wiley. 1996.
[7] Glenn W. Stagg, El Abiad A. H. Computer Methods in Power Systems Analysis. McGraw-Hill. 1981.
[8] Hingorani N.G. High Power Electronics and Flexible AC Transmission System, Power Engineering Review. *IEEE*. 1988.
[9] Shaoyun Ge., Chung T. S. *Coupled active dispatch with FACTS Devices and Specified Power Flow Control Constraints*. Proceedings of the 4th International Conference on Advances in Power System Control, APSCOM 97. HONG KONG. 1997; 2: 678-683.
[10] Lu Y., Abur A. Static Security Enhancement via Optimal Utilization of Thyristor-Controlled Series Capacitors. *IEEE Trans. Power System*. 2002; 17(2): 324-329.
[11] Abdel-Moumen M. A., Padhy N. P. *Power Flow Control and Transmission Loss Minimization Model with TCSC for Practical Power Networks*. IEEE Proceeding. 2003: 880-884.
[12] Feurt-Esquivel C. R., Acha E., and Ambriz-Pérez H. A Thyristor Controlled Series Compensator Model for the Power Flow Solution of Practical Power Networks. *IEEE Trans. Power Systems*. 2000; 15(1): 58-64.
[13] Rosehart W. D., Canizares C. A., and Quintana V. H. Effect of Detailed Power System Models in Traditional and Voltage Stability Constrained Optimal Power Flow Problems. *IEEE Trans. Power Systems*. 2003; 18(1): 25-35.
[14] Moghavvemi M., Faruque M.O. *Effects of FACTS Devices on Static Voltage Stability*. IEEE Proceeding. 2000: 357-362.
[15] Differential Evolution [Online], Available: http://www.icsi.berkeley.edu/~storn/code.html, 2008.